A new approach to estimating the albedo for snow-covered surfaces in the satellite UV method

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Received 10 February 2003; revised 30 April 2003; accepted 8 May 2003; published 4 September 2003.

[1] This paper describes a new method for estimating snow albedo for satellite retrieval of surface UV irradiance and daily UV doses over snow-covered terrains. The method is based on combining satellite and meteorological analysis data. The satellite data exploited in this work are the measured reflectivities of the Total Ozone Mapping Spectrometer/Nimbus 7 instrument that coincides with the European Centre for Medium-Range Weather Forecasts ERA-15 reanalyzed meteorological data. We compared satellite-retrieved UV daily doses to the ground-based measurements of two Finnish and five Canadian sites. The comparison clearly showed that the new snow albedo approach improves the accuracy of the satellite-retrieved UV doses. *INDEX TERMS:* 3359 Meteorology and Atmospheric Dynamics: Radiative processes; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 3367 Meteorology and Atmospheric Dynamics: Theoretical modeling; *KEYWORDS:* ultraviolet radiation, snow albedo, satellite estimates of UV irradiance, reflectivity

Citation: Arola, A., J. Kaurola, L. Koskinen, A. Tanskanen, T. Tikkanen, P. Taalas, J. R. Herman, N. Krotkov, and V. Fioletov, A new approach to estimating the albedo for snow-covered surfaces in the satellite UV method, *J. Geophys. Res.*, *108*(D17), 4531, doi:10.1029/2003JD003492, 2003.

1. Introduction

[2] At high latitudes and in mountainous regions snow albedo is a significant factor affecting the intensity of UV radiation at the surface. While the largest doses of UV irradiance usually occurs during the summer months, the sensitivity of biological systems to UV doses also varies with season. For some organisms the maximum sensitivity occurs near the end of winter and during the spring months, while the organisms are immature and in their maximum growth phases. An increase of the ground albedo can enhance the clear-sky global UV irradiance substantially (up to about 30%). This increase in irradiance is due to the reflection and backscattering between the snow surface and the atmosphere. Under a cloudy sky this amplifying effect of snow becomes even stronger [*Lenoble*, 1998; *Herman et al.*, 1999; *Smolskaia et al.*, 1999; *Kylling et al.*, 2000] because of the enhanced backscattering.

[3] The visible and UV albedos are usually above 0.80 for new and relatively fresh snow and around 0.50–0.60 for older snow. The albedo of pure snow is usually assumed to depend on depth, age and temperature [*Wiscombe and Warren*, 1980; *Grenfell et al.*, 1994; *Feister and Grewe*, 1995]. However, the effects of these factors are strongly wavelength-dependent. In the UV region snow albedo has practically no dependence on the structure of snow crystals [*Wiscombe and Warren*, 1980; *Chýleck et al.*, 1983]. *Grenfell et al.* [1994] also studied the reflection of solar radiation by the Antarctic snow surface at a wavelength range of 300–2500 nm. They found that the albedo had a uniform value of 0.96–0.98 across the UV and visible spectrum and, at this wavelength range, it was nearly independent of snow grain size and solar zenith angle.

[4] The values obtained with the ground-based measurements of snow albedo are not directly applicable for the satellite UV methods. Typically such a measurement concerns a small unbroken homogeneous area, whereas the footprint of a spaceborne instrument is much larger, inhomogeneous and often only partly covered by snow. Therefore the high albedo values measured by *Grenfell et al.* [1994], *Feister and Grewe* [1995], and *Blumthaler and Ambach* [1988] are only rarely representative for the ground surface areas within a satellite instrument field of view. A typical reflectivity value of recently snow-covered clear-sky Total Ozone Mapping Spectrometer (TOMS) scene containing trees and roads is about 0.4 [*Herman et al.*, 1999].

[5] *Herman and Celarier* [1997] have constructed an albedo climatology based on the measurements of TOMS/

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0148-0227/03/2003JD003492

Nimbus 7 over the period of 1978–1993. This so-called Minimum Lambertian Equivalent Reflectivity (MLER) data represent the minimum daily reflectivities on a global grid over this 15-year time period. It is obvious that this type of climatology systematically excludes the snow-covered scenes in favor of snow-free conditions. This omission is strongly emphasized in the surfaces that naturally have yearly winter and spring time snow cover. The actual time difference of snowmelt for two different years at the same site may be of several weeks. This means that the MLER data, representing the very minimum of the reflectivity measurements at a given location and time of the year, does not capture these daily or interannual variations.

[6] The TOMS UV algorithm for estimating the surface UV irradiance from the satellite measurements proceeds in two steps: first the clear-sky radiation is calculated, which is then adjusted by the cloud transmission factor [*Herman et al.*, 1999; *Krotkov et al.*, 1998, 2001]. For the snow surface albedo the algorithm uses the value of MLER or 0.4, whichever is bigger, for cases where the snow climatology indicates snow on the ground with 50% probability. If the actual measured reflectivity is higher than that, the additional reflectivity is assigned to cloud cover. Unfortunately this technique leads to a bias when MLER underestimates the actual surface albedo and assigns the excess reflectivity to clouds, resulting in underestimation of surface UV irradiance [*Kalliskota et al.*, 2000; *Kylling et al.*, 2000]. The objective of this study was to develop and test an improved approach to estimate the regional snow albedo for the TOMS UV algorithm.

2. Improved Snow Albedo Treatment

[7] As stated earlier, one of the main shortcomings of the current TOMS UV algorithm is its inability to distinguish snow (or ice) from clouds. Therefore, with the use of TOMS reflectivity data alone, the actual temporal and spatial variability in surface albedo cannot be taken into account. To overcome this problem, our goal was to develop a parameterization that takes the surface albedo variability into account by using external data. The main idea of our approach was to find a relationship that connects the information of meteorological parameters to the snow surface albedo in UV. For this purpose, we used European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-15 snow cover data as an independent data source. These data were interpolated to the resolution of gridded TOMS reflectivity data, i.e., 1.25° in longitude by 1.0° in latitude.

[8] Instantaneous fields of snow depth, total cloud cover and 2-m temperature were interpolated from the ECMWF Era15 Gaussian grid to the grid of TOMS data using MARS (Meteorological Archival and Retrieval System) postprocessing facilities. The analysis was made with a 3-hour temporal resolution. Therefore the 6-hour analyses and intervening short 3-hour forecast fields were used to compile the data set used in this study.

[9] Our approach can be divided into two main steps.

[10] 1. Since TOMS reflectivity measurements are affected by the cloud-surface system, we wanted to select only those values that corresponded to the cloud-free and snow-covered case, according to the ECMWF data. Since only the clear-sky reflectivity measurements were picked up, the assumption was made that they are measurements of surface reflectivity during snow cover, not affected by clouds. In other words, the resulting set contained the data rows (for each pixel of gridded TOMS reflectivity data set): clear-sky reflectivity measurement followed by corresponding ERA15 data, for example, snow depth, snow age, and 2-m temperature.

[11] 2. As a next step, we determined for the best possible multiple regression form between TOMS clear-sky reflectivity and several snow-related independent variables, each separately and in every combination. We used data from two Finnish stations: Jokioinen, Sodankylä and five Canadian stations: Saskatoon, Edmonton, Winnipeg, Toronto and Churchill, since the ground-based UV measurements and various ancillary data for the validation purposes were available.

[12] The regional snow albedo in the UV spectral range depends mainly on the fractions of snow-covered and snow-free parts of the ground, and to a lesser extent on the snow quality, on contamination in particular. It has been suggested in an earlier study [*Schwander et al.*, 1999] that the main parameters that explain the variability of regional albedo are the snow depth and the age of snow. We tested several parameters to determine the reflectivity in our data set. The variability in the reflectivity at any given location can be thought as a twofold problem. First, the mean reflectivity has to be correct, because it depends strongly on the terrain type. For example, the TOMS mean clear-sky reflectivity from the snow surface at the pixel including Churchill is 0.75, while it is 0.37 at Toronto. Second, there is time variability of regional snow albedo at any given location, from changes in snow depth and snow quality, for instance.

[13] We found the snow depth as the most crucial parameter in explaining the time variability of the regional albedo at any particular pixel. Moreover, the relationship was nonlinear, unlike in the study by *Schwander et al.* [1999].

[14] The reason for testing 2-m air temperature as an explaining variable was that a linear albedo-temperature relationship has been confirmed using the albedo measurements, when the temperature is close or above °C, indicating decreased snow albedo at the melting stage [*Roesch et al.*, 1999]. However, in our data set there was no evidence of this behavior; the 2-m air temperature as an independent variable improved the fit only slightly when compared to the snow depth alone. This is most likely due to differences in the spectral region and the effective areas between our study and that of *Roesch et al.* [1999].

[15] When the age of snow was included as an independent variable of the multiple regression, together with the snow depth, the fit was improved even less than with the 2-m air temperature. This contradicts the study by *Schwander et al.* [1999], who established their linear regression with snow depth and the age of snow as independent variables. We then confirmed our results from the ECMWF snow parameters and the TOMS reflectivity using measurements of snowfall at stations of Jokioinen and Sodankylä. We also analyzed the snow fall measurements within an area typical for TOMS pixel, i.e., stations as much as 100 km apart. The analysis suggested that it is difficult to define a unique snow age parameter for such a large area.

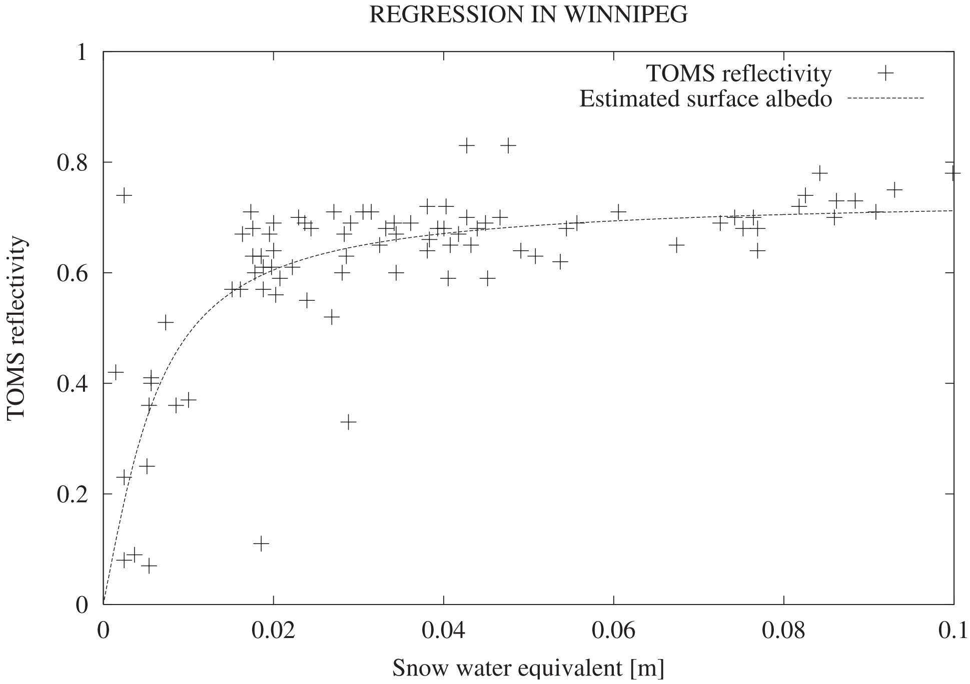

Figure 1. Clear-sky TOMS reflectivity as a function of the snow depth (*SWE*) in Winnipeg, Canada.

[16] Once we established that the data from Finnish and Canadian stations resulted in a nonlinear regression between reflectivity and snow depth, we extended our analysis to determine the best fit relationship and degree of nonlinearity on a global basis. We defined the following model between the reflectivity and snow depth:

$$R_s = R_{max} * \frac{2}{\pi} * \arctan(c * SWE), \quad (1)$$

where R_s is the TOMS clear-sky reflectivity, *SWE* is the corresponding snow water equivalent (in meters) from the ECMWF model data and R_{max} and c are constants estimated separately for the data set of each pixel. For instance, the final results in the pixel including Winnipeg are shown in Figure 1. R_{max} and c account for separate effects and vary from location to location. R_{max} is the level of saturation for the reflectivity estimate, while c accounts for the rate at which this level is reached. They take into account the characteristics of each location, for example, the type of

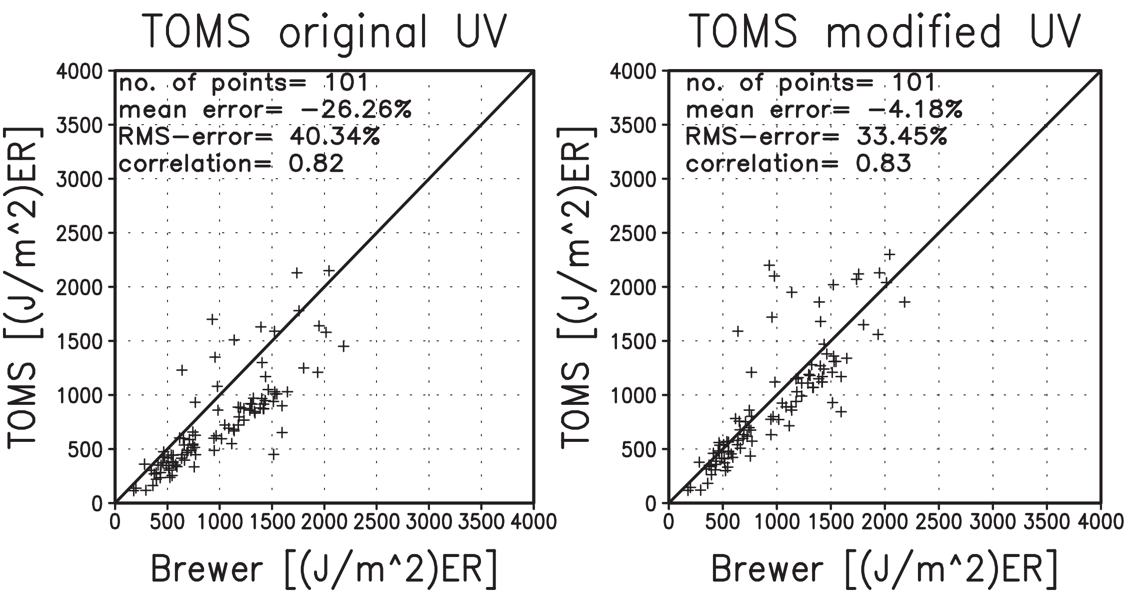

Figure 2. Comparison of daily erythemal irradiation, weighted according to the action spectrum by CIE87, estimated by the TOMS UV algorithm and Brewer measurements at Sodankylä: (left) original snow albedo approach and (right) improved snow albedo based on equation (1).

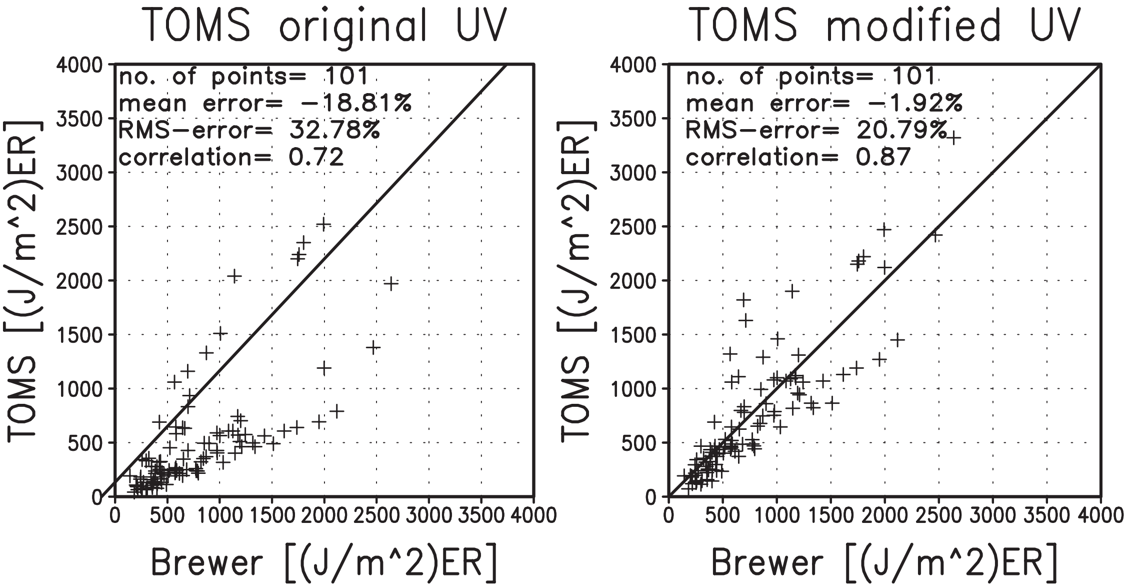

Figure 3. Comparison of daily erythemal irradiation, weighted according to the action spectrum by CIE87, estimated by the TOMS UV algorithm and Brewer measurements at Winnipeg: (left) original snow albedo approach and (right) improved snow albedo based on equation (1).

terrain, its homogeneity, and typical amounts of accumulated snow. We want to emphasize that our form prevents the reflectivity estimate from exceeding the value 1.

[17] It should be noted that our parameterization is quite robust, since the only independent variable is a time-integrated measure, while if a variable such as the number of days since the last snowfall, i.e., the age of snow, was included, the albedo estimate would be much more sensitive to possible errors in the supporting data, regardless of whether they were random or systematic. Moreover, one of the advantages of this approach is that it can also be applied with other global snow depth data. However, in that case a new set of R_{max} and c needs to be estimated, to incorporate the effects of resolution and type of the snow depth data that is used.

3. Validation Results

[18] We tested the new approach by comparing the daily erythemal irradiation, weighted according to the action spectrum by CIE87 [*McKinlay and Diffey*, 1987], estimated by the TOMS UV algorithm with both the current and improved snow albedo approach, against ground-based measurements. Figure 2 (left) shows the results of the

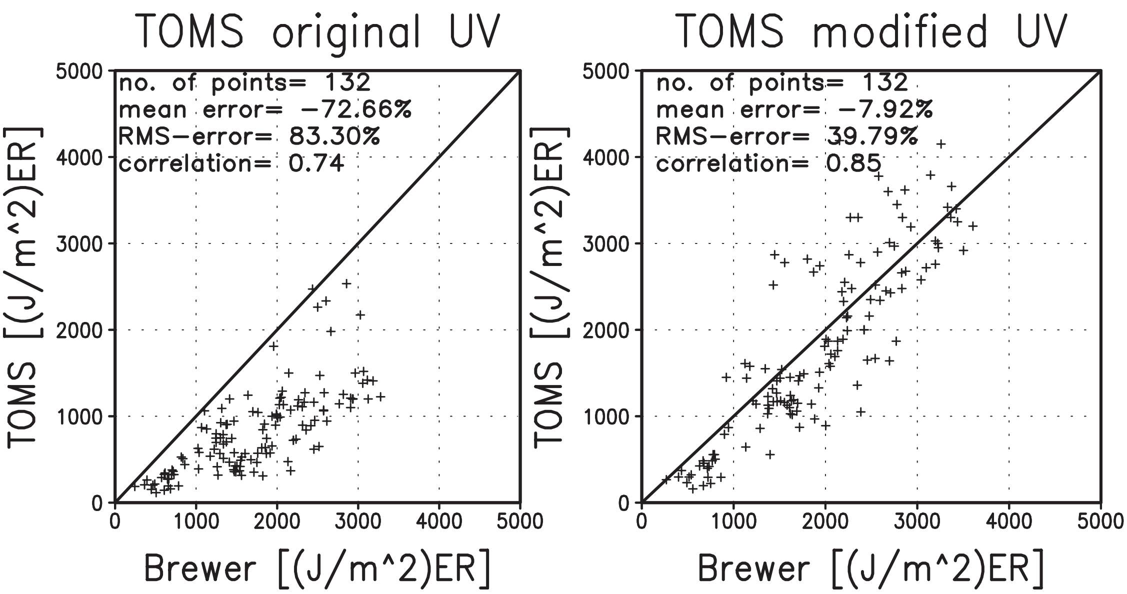

Figure 4. Comparison of daily erythemal irradiation, weighted according to the action spectrum by CIE87, estimated by the TOMS UV algorithm and Brewer measurements at Churchill: (left) original snow albedo approach and (right) improved snow albedo based on equation (1).

original algorithm and the right one the improvement obtained with the new snow albedo treatment at Sodankylä. Only the cases with snow cover are included, and the validation period covers years 1992 and 1993. The statistics of the differences in percentage between satellite- and ground-based UV are shown in the figures. The albedo estimates, based on the snow depth data, improve the satellite UV data. The mean error in particular, is reduced.

[19] Figure 3 demonstrates the performance of our parameterization at Winnipeg. It is evident that the original algorithm underestimates the surface UV more strongly than at Sodankylä, since the average reflectivity is 0.66 at Winnipeg, while it is 0.52 at Sodankylä.

[20] Figure 4 shows the results at Churchill. There is a strong difference between the original and new approach, implying that the original method has deficiencies particularly in those locations where the mean reflectivity and year-to-year variability is high. In those locations the MLER approach strongly underestimates the surface albedo, particularly during the snowmelt period. As a consequence, erroneous cloudiness is assumed and thus the surface UV irradiance is clearly underestimated.

4. Conclusions

[21] We have developed a simple snow depth based model of snow albedo for TOMS UV algorithm. The model applies the ECMWF data as an independent source of snow effect data.

[22] It is stressed that this simple parameterization is rather robust, since the only independent variable is not sensitive to instantaneous errors in meteorological model data, as would be the case if the snow age was included.

[23] We compared the new approach to ground-based measurements, and clear improvements were demonstrated at all the validation sites. The current algorithm underestimates surface UV irradiance in those locations where typically the surface reflectivity is high (e.g., Churchill) and where spring time snowmelt periods differ from year to year. The new approach solves this problem and removes the systematic bias in spring time surface UV irradiance.

References

Blumthaler, M., and W. Ambach, Solar UVB albedo of various surfaces, *Photochem. Photobiol.*, *48*, 85–88, 1988.

Chýleck, P., V. Ramaswamy, and V. Srivastava, Albedo of soot-contaminated snow, *J. Geophys. Res.*, *88*, 10,837–10,843, 1983.

Feister, U., and R. Grewe, Spectral albedo measurements in the UV and visible region over different types of surfaces, *Photochem. Photobiol.*, *62*, 736–744, 1995.

Grenfell, T. C., S. G. Warren, and P. C. Mullen, Reflection of solar radiation by the Antarctic snow surface at ultraviolet, visible, and near-infrared wavelengths, *J. Geophys. Res.*, *99*, 18,669–18,684, 1994.

Herman, J. R., and E. A. Celarier, Earth surface reflectivity climatology at 340 nm to 380 nm from TOMS data, *J. Geophys. Res.*, *102*, 28,003–28,011, 1997.

Herman, J. R., N. Krotkov, E. Celarier, D. Larko, and G. Labow, Distribution of UV radiation at the Earth's surface from TOMS-measured UV-backscattered radiances, *J. Geophys. Res.*, *104*, 12,059–12,076, 1999.

Kalliskota, S., J. Kaurola, P. Taalas, J. R. Herman, E. Celarier, and N. Krotkov, Comparison of daily UV doses estimated from Nimbus-7/TOMS measurements and ground-based spectroradiometric data, *J. Geophys. Res.*, *105*, 5059–5067, 2000.

Krotkov, N., P. K. Bhartia, J. R. Herman, V. Fioletov, and J. Kerr, Satellite estimation of spectral surface UV irradiance in the presence of tropospheric aerosols: 1. Cloud-free case, *J. Geophys. Res.*, *103*, 8779–8793, 1998.

Krotkov, N. A., J. R. Herman, P. K. Bhartia, V. Fioletov, and Z. Ahmad, Satellite estimation of spectral surface UV irradiance: 2. Effects of homogeneous clouds and snow, *J. Geophys. Res.*, *106*, 11,743–11,760, 2001.

Kylling, A., A. Dahlback, and B. Mayer, The effect of clouds and surface albedo on UV irradiances at a high latitude site, *Geophys. Res. Lett.*, *27*, 1411–1414, 2000.

Lenoble, J., Modeling of the influence of snow reflectance on ultraviolet irradiance for cloudless sky, *Appl. Opt.*, *37*, 2441–2447, 1998.

McKinlay, A. F., and B. I. Diffey, A reference action spectrum for ultraviolet induced erythema in human skin, *J. Int. Comm. Illum.*, *6*, 17–22, 1987.

Roesch, A., H. Gilgen, M. Wild, and A. Ohmura, Assessment of GCM simulated snow albedo using direct observations, *Clim. Dyn.*, *15*, 405–418, 1999.

Schwander, H., B. Mayer, A. Ruggaber, A. Albold, G. Seckmeyer, and P. Koepke, Method to determine snow albedo values in the UV for radiative transfer modelling, *Appl. Opt.*, *38*, 3869–3875, 1999.

Smolskaia, I., M. Nunez, and K. Michael, Measurement of erythemal irradiance near Davis station, Antarctica: Effect of inhomogeneous surface albedo, *Geophys. Res. Lett.*, *26*, 1381–1384, 1999.

Wiscombe, W. J., and S. G. Warren, A model for the spectral albedo of snow I: Pure snow, *J. Atmos. Sci.*, *37*, 2712–2733, 1980.

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